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Predicting the Pressure Driven Flow of Gases Through Micro-Capillaries and Micro-Orifices

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ABSTRACT

A large body of experimentally measured gas flow rates were obtained from the literature and then compared to the predictions obtained with constitutive flow equations. This was done to determine whether the equations apply to the predictions of gas flow rates from leaking containment vessels used to transport radioactive materials. The experiments consisted of measuring the volumetric pressure-driven flow of gases through micro-capillaries and micro-orifices. The experimental results were compared to the predictions obtained with the equations given in ANSI N14.5 the *American National Standard for Radioactive Materials-Leakage Tests on Packages for Shipment.*

The equations were applied to both 1) the data set according to the recommendations given in ANSI N14.5 and 2) globally to the complete data set. It was found that:

- The continuum and molecular flow equation provided good agreement between the experimental and calculated flow rates for flow rates less than about 1 atm·cm^3/s.
- The choked flow equation resulted in over-prediction of the flow rates for flow rates less than about 1 atm·cm^3/s.
- For flow rates higher than 1 atm·cm^3/s, the molecular and continuum flow equation over-predicted the measured flow rates and the predictions obtained with the choked flow equation agreed well with the experimental values.

Since the flow rates of interest for packages used to transport radioactive materials are almost always less than 1 atm·cm^3/s, it is suggested that the continuum and molecular flow equation be used for gas flow rate predictions related to these applications.

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EXECUTIVE SUMMARY

The equations suggested for modeling gas flow in ANSI N14.5, the *American National Standard for Radioactive Materials-Leakage Tests on Packages for Shipment*, are evaluated to determine their applicability for predicting gas flow rates through micro-capillaries and micro-orifices (leak hole diameters between 0.1 and 100 μm). The equations are evaluated by comparing the gas flow rate predictions to a large body of experimentally measured gas flow rates obtained from the literature. These gas flow rate experiments were conducted by measuring the flow of gas through manufactured capillary and orifice leak holes which ranged in size from 0.5 to 250 μm in diameter. The pressure drop across the leak holes ranged from 1 psi to 1000 psi. Typically, the downstream pressure was atmospheric; however, some experiments were performed with sub-atmospheric downstream pressures.

ANSI N14.5 recommends use of equations describing molecular and continuum flow, and also choked flow. The standard gives criteria for determining the appropriate predictive equation for a particular flow situation. The flow rate predictions obtained with the constitutive equations are compared to the experimentally measured gas flow rate in two distinct ways: (1) the equations were applied to the flow situations according to the recommendations given in ANSI N14.5, and (2) the predictive equations were applied globally to the complete data set.

Comparison of the predicted and measured values resulted in clear generalities regarding the applicability of the equations to a particular flow situation. It was found that:

- For flow rates less than 1 atm·cm^3/s, the molecular and continuum flow equation provided predictions that agreed well with the experimental results and that the choked flow equation resulted in over predictions of the gas flow rates by up to four orders of magnitude.
- For flow rates higher than 1 atm·cm^3/s, the situation was reversed with the choked flow equation providing predictions that agreed well with the experimental results and the molecular and continuum flow equation resulting in over predictions of the gas flow rates.

Therefore, for applications related to modeling the gas leakage rates from containers used to transport radioactive materials, which usually involves prediction of gas flow rates less than 1 atm·cm^3/s, it is recommended that the molecular and continuum flow equations be used.

PREDICTING THE PRESSURE-DRIVEN-FLOW OF GASES THROUGH MICRO-CAPILLARIES AND MICRO-ORIFICES

1. INTRODUCTION

1.1 Background

ANSI N14.5[1] describes the fluid dynamic models currently used to predict gas leakage related to leakage acceptance criteria for packages used to transport radioactive materials. This standard recommends that the flow be modeled with equations describing choked flow or continuum and molecular flow. The fluid properties and extrinsic conditions are used to determine the appropriate flow regime, as described below.

1.2 Scope and Objective

In this paper, the equations suggested in ANSI N14.5 for modeling gas flow are evaluated to determine their applicability for predicting gas flow rates through micro-capillaries and micro-orifices (leak hole diameters between 0.1 and 100 µm). The equations are evaluated by comparing the gas flow rate predictions to a large body of experimentally measured gas flow rates. These gas flow rate experiments were conducted by measuring the flow of gas through manufactured capillary and orifice leak holes which ranged in size from 0.5 to 250 µm in diameter. The pressure drop across the leak holes ranged from 1 psi to 1000 psi. Typically, the downstream pressure was atmospheric; however, some experiments were performed with sub-atmospheric downstream pressures.

With the aim of determining the leakage rate of powdered radioactive oxides from shipping packages, some of the experiments were conducted with powder suspended in the gas to form an aerosol. The powdered aerosol was formed either by agitation of the test container or by injection of a gas under the powder. Plutonium oxide and depleted uranium oxide were used as powdered test materials. For purposes of predicting gas and powder flow rates, the powder was assumed to be completely entrained in the leaking gas with the powder not changing any of the gases rheological properties.

[1]*American National Standard for Radioactive Materials Leakage Teats on Packages for Shipment.* ANSI N14.5-1987.

2. FLOW EQUATIONS

2.1 Molecular Flow

When the mean-free path of the gas molecule is on the order of the leak hole diameter, the flow is modeled as molecular flow. Using kinetic gas theory, Knudsen's law for free molecular flow can be derived:

Equation E-1

$$L_m = \frac{3.81x10^3 D^3 \sqrt{T/M}}{aP_a}(P_u - P_d)$$

where:

- D is the capillary diameter [cm],
- a is the capillary length [cm],
- P_a is the average pressure [atm],
- P_u is the upstream pressure [atm],
- P_d is the downstream pressure [atm],
- T is the temperature [°K],
- M is the molecular weight [g/mole], and
- L_m is the gas leakage rate [cm^3/s] due to molecular flow at the average pressure.

To determine the flow rate due to molecular flow entering the flow path at the upstream pressure, the density correction is equivalent to multiplying the flow rate given by Equation E-1 by P_a/P_u. To determine the volumetric flow rate at 1.0 atmosphere (atm·cm^3/s), multiply the flow rate given by Equation E-1 by the average pressure, P_a/1 atm.

2.2 Continuum Flow

Starting with the equations of motion, Poiseuille's law for continuum flow can be derived. For continuum flow, the leak hole diameter is significantly larger than the mean free path of a gas molecule. The form of this equation used in ANSI N14.5 for the modeling of continuum flow is:

Equation E-2

$$L_v = \frac{2.49x10^6 D^4}{a\mu}(P_u - P_d)$$

where:

μ is the gas viscosity (cP),

D is the capillary diameter [cm],

a is the capillary length [cm],

P_u is the upstream pressure [atm],

P_d is the downstream pressure [atm], and

L_v is the volumetric flow rate [cm^3/s] due to continuum flow at the average pressure.

To determine the flow rate due to continuum flow entering the flow path at the upstream pressure, the density correction is equivalent to multiplying the flow rate given by Equation E-2 by P_a/P_u. To determine the volumetric flow rate at 1.0 atmosphere, multiply the flow rate given by Equation E-2 by the average pressure, P_a/1atm.

2.3 Continuum and Molecular Flow

Equations E-1 and E-2 can be combined to give the resultant flow rate when there are contributions from continuum flow and from molecular flow:

Equation E-3

$$L_{m+v} = \left[\frac{2.49x10^6 D^4}{a\mu} + \frac{3.81x10^3 D^3\sqrt{T/M}}{aP_a}\right](P_u - P_d)$$

This composite equation can be used if the flow is dominated by either continuum or molecular flow. When one flow regime dominates, the term for the other flow regime will result in an insignificant contribution. During transitional flow, there will be contributions to the total flow from both flow regimes. The flow rate calculated with Equation E-3 is at the average pressure, as noted previously. The flow rate at the upstream pressure is obtained by multiplying Equation E-3 by the ratio P_a/P_u.

2.4 Choked Flow

For flow conditions where there is a relatively large pressure drop and a relatively large leak hole diameter, ANSI N14.5 recommends use of the choke flow equation for gas leakage rate predictions. For large pressure differences across the leak hole when the flow rate approaches the sonic limit, the flow is choked. The equation for choked flow is:

Equation E-4

$$L_u = \frac{\pi D^2}{4}\sqrt{\frac{2kR_oT_u}{M(k+1)}}\left(\frac{2}{k+1}\right)^{[1/(k-1)]}$$

where:

D is the capillary diameter [cm],

T_u is the upstream temperature [°K],

M is the molecular weight [g/mole],

R_o=8.31x10^7 erg/mole·°K (the universal gas constant),

k is the ratio of specific heat at constant pressure to specific heat at constant volume, and

L_u is the volumetric flow rate [cm^3/s] due to choked flow at the upstream temperature and pressure.

To determine the volumetric flow rate at 1.0 atmosphere, multiply Equation the flow rate given by Equation E-3 by the upstream pressure, P_u/1 atm.

2.5 Determination of Flow Regime

Before a constitutive equation can be applied to a particular flow situation, the flow regime must be determined so that the appropriate equation can be chosen. There are two terms used as indicators of the flow regime:

(1) r_f, which is the ratio of the laminar flow contribution to the molecular flow contribution, and

(2) r_c, which is the critical pressure ratio.

The ratio of laminar flow to molecular flow, r_f, is given by:

Equation E-5

$$r_f = \frac{L_v}{L_m} = \frac{654DP_a}{\mu\sqrt{T/M}},$$

and the critical pressure ratio, r_c, is given by:

Equation E-6

$$r_c = \left(\frac{2}{k+1}\right)^{[k/(k-1)]},$$

where:

r_c=0.528 for air,

r_c=0.487 for helium, and

k is the ratio of specific heat at constant pressure to specific heat at constant volume.

There are three distinct flow regimes used in calculating leakage rates:

- If $(P_d/P_u) \leq r_c$ and $r_f \geq 1$, then the flow is choked [use Eqn. E-4]
- If $(P_d/P_u) \leq r_c$ and $r_f < 1$, then the flow is molecular-dominated [use Eqn. E-3]
- If $(P_d/P_u) > r_c$, then the flow is molecular and laminar [use Eqn. E-3]

3. COMPARISON OF CALCULATED AND MEASURED FLOW RATES

3.1 Description of Experiments

Many research teams have conducted measurements of the flow rate of gases through micro-capillaries and micro-orifices[3-23]. Most of these experiments were conducted by measuring the flow rate of gas that escaped from a container that had a manufactured leak hole, either a capillary or an orifice. For the larger flow rates, the bubble rise technique was used to measure the flow rate, but for the smaller flow rates, mass spectroscopy was used. Typically, the pressure inside the container was maintained at a constant value above atmospheric pressure.

Since some of these studies were aimed at determining the release rate of powdered radioactive materials from packages used for transportation, a portion of the data collected was from systems where powders were suspended in the test gases. In particular, some of the data from Schwendiman, *et al.*, was from experiments that included PuO_2 or depleted UO_2. These experiments that included powder suspended in the gas were conducted with the leak hole situated either under the static powder level or with the leak hole situated above the static powder level. Since the leak hole was commonly plugged during experiments where the leak hole was situated under the static powder level, only experiments where the leak hole was situated above the static powder level or experiments with no powder present were included.

In the experiments performed by Morton *et al.*, glass micro-spheres with diameters ranging from 2 to 20 μm where suspended in the leaking gas. The glass micro-sphere aerosols were generated using a fluidized-bed mounted at the base of the pressure chamber. The high-pressure side to the leakage path was maintained at 100±1 kPa (approximately 1 atmosphere) above ambient pressure. In addition to these leakage tests, the capillary was tested after each run with pure gas to ensure that partial plugging did not occur. In every case, the final standard leakage rate value was similar to the initial leakage rate, confirming that the glass micro-spheres had not obstructed the leakage pathway. The data presented by Mitchell *et al.*, was obtained with the same experimental set-up and operating conditions as those used by Morton *et al.*

In the work headed by Owzarski, no particles were suspended in the leaking gas; however, the effect of capillary surface roughness on gas flow rate was examined. In these experiments, the upstream pressure was held at a constant value within the range 1 to 1000 psig, the capillary lengths varied between 0.76 to 2.54 cm, and the capillary diameters were in the range of 48 to 275 μm. For all the experiments, the downstream pressure was one atmosphere. Although the capillary diameters and the resulting gas flow rates in these experiments are typically higher than those relevant to leakage paths in packages used to transport radioactive materials, comparison of these measured flow rates to those predicted by the constitutive equations is instrumental in determining the range of applicability of the predictive equations.

Sutter *et al.*, performed some flow rate experiments using micro-orifices with diameters ranging from 20 to 200 μm. No particles were suspended in the gas for these experiments. For most of the orifices, the length-to-diameter ratio of the leakage path was less than one; however, for the smallest orifices, the L/D ratio was about 10. The upstream pressure was maintained at a constant value within the range of 1 to 100 psig, and the down stream pressure was one atmosphere. Variable area flow meters were used to measure the downstream flow rate. These flow meters had a minimum detection level of 0.02 cm^3/min and an accuracy of approximately ±10%. Using essentially the same experimental set-up, Sutter *et al.*, performed other leak-rate experiments where depleted uranium oxide was suspended in the leaking gas. The data from these experiments—where the leak path was situated above the static powder level—were included in this analysis.

Hedley *et al.*, performed gas and liquid leak-rate experiments using capillaries with diameters between 1.5 and 60 μm. The lengths of the capillaries varied between 100 and 4000 times the capillary diameters. No particles were suspended in the leaking fluids for these experiments. The upstream and downstream pressures were held constant during the course of an experimental run. The upstream pressures ranged from 1 to 4 atmospheres, and the downstream pressures ranged from 0 to 1 atmospheres. The results obtained from these experiments are particularly relevant to the leakage rates, leak hole diameters, and pressure differentials important for packages used to transport radioactive materials.

3.2 Use of Predictive Equations as Specified in ANSI N14.5

Figure 1 shows a plot of the measured flow rate versus the ratio of the predicted flow rate to the measured flow rate. In this plot, the appropriate equation was applied to each data point by first determining the gas flow regime (as outlined above) from the experimental conditions and the gas used (helium or air). A value of one for the ratio of predicted gas flow rate to measured gas flow rate indicates agreement between the calculated and experimentally measured results. All the flow rates were converted to units of atm·cm^3/s for purposes of comparison.

From Figure 1, it is clear that the data points form two distinct branches. The branches are coincident where the measured flow rate is about 1 atm·cm^3/s or larger. However, the branches diverge for lower flow rates (less than 1 atm·cm^3/s) with one branch showing a progressively greater deviation as the measured flow rate is reduced, and the other branch showing good agreement between the calculated and measured flow rates.

Since gas flow rates of interest are generally below 10^{-2} atm·cm^3/s for purposes of leak testing packages used to transport radioactive materials, the experiments in this range from Figure 1 are re-plotted in Figure 2 to show more detail. From Figure 2, it is clear that the upper branch of data indicates an over-prediction by at least an order-of-magnitude, whereas the lower branch of data shows generally good agreement with the largest deviations of the predicted values to the experimental values being within a factor of 4.

As shown in Figures 1 and 2, a significant number of experimental results were not predicted well following the generally accepted criteria for determining the appropriate flow regime and related predictive equation. Although the vast majority of the discrepancies resulted in an over-prediction of the flow rate by the equations, the amount of over-prediction exhibited is in excess of the conservatism required for most engineering applications.

3.3 A Modified Approach to Application of the Predictive Equations

In an effort to identify an equation that would provide more accurate predictions of the measured gas flow rates, the two equations used (choked, and laminar & molecular) were applied globally to the complete data set. Figure 3 shows a plot of the measured flow rate versus the ratio of the predicted flow rate to the measured flow rate, where the choked flow equation and the equation for laminar and molecular flow were applied to all the experimental results. The solid data points correspond to predictions using the laminar and molecular flow equation, and the open data points correspond to predictions using the choked flow equation.

Similar to Figure 1, Figure 3 shows two distinct branches of data. The branch generated with the choked flow equation shows over-predictions for measured flow rates less than approximately 1 atm·cm^3/s and generally good agreement with the experimental values for flow rates greater than about 1 atm·cm^3/s. The data generated with the laminar and molecular flow equation generally show good agreement for flow rates less than 1 atm·cm^3/s and a large degree of over-prediction for flow rates greater than about 1 atm·cm^3/s.

To examine the data shown in Figure 3 in more detail, the data is re-plotted in Figure 4 to show the lower flow rate region of interest (flow rates between 10^{-8} and 10^{-2} atm·cm^3/s). From Figure 4, it is clear the equation for laminar and molecular flow almost always provides a better prediction of the measured flow rate than the choked flow equation, regardless of the predetermined flow regime. The only drawback in using the laminar and molecular flow equation to predict gas flow rates for all the flow conditions is that it sometimes provides an under-prediction. The maximum amount of under-prediction is about an order-of-magnitude. However, when the choked flow equation is used to predict the gas flow rates, there is essentially always an over prediction. For measured flow rates of 10^{-6} atm·cm^3/s, the choked flow equation over predicts the gas flow rate by 2 to 4 orders-of-magnitude. This over prediction may be a consequence of friction or other surface phenomena in a long slender passage since viscous dissipation is not accounted for in the equation for choked flow.

4. CONCLUSIONS

Predictions of gas flow rates through micro-capillaries and micro-orifices made with two constitutive equations, an equation for choked flow and an equation for laminar and molecular flow, were compared to a large set of experimental results. In general, when the two equations were applied globally to the complete experimental data set, the predictions of the laminar and molecular flow equation agreed well with the experimental results for relatively low standard flow rates. The predictions obtained using the choked flow equation agreed well with the experimental results for flow rates larger than about 1 atm·cm^3/s and gave over predictions for flow rates less than about 1 atm·cm^3/s, whereas the equation for laminar and molecular flow provided predictions that agreed well with experimental results for flow rates less than about 1 atm·cm^3/s and gave over predictions for flow rates larger than about 1 atm·cm^3/s. In light of the above results, the equation which results in the most accurate prediction of the flow rate is:

- The choked flow equation (Eqn. E-4) for $L_{std} \geq 1$ atm·cm^3/s
- The laminar and molecular flow equation (Eqn. E-3) for $L_{std} < 1$ atm·cm^3/s

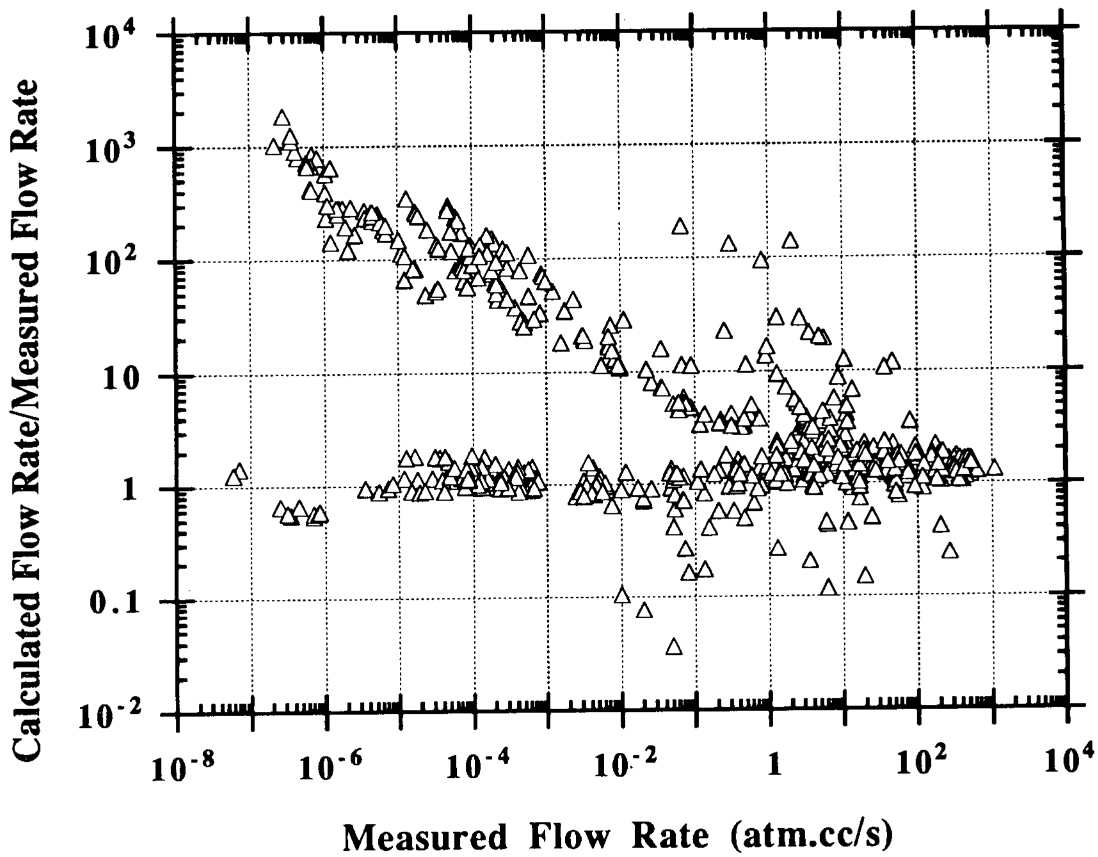

Figure 1. Measured gas flow rates versus the ratio of predicted gas flow rates to measured gas flow rates. The predictive equations were applied as specified in ANSI N14.5.

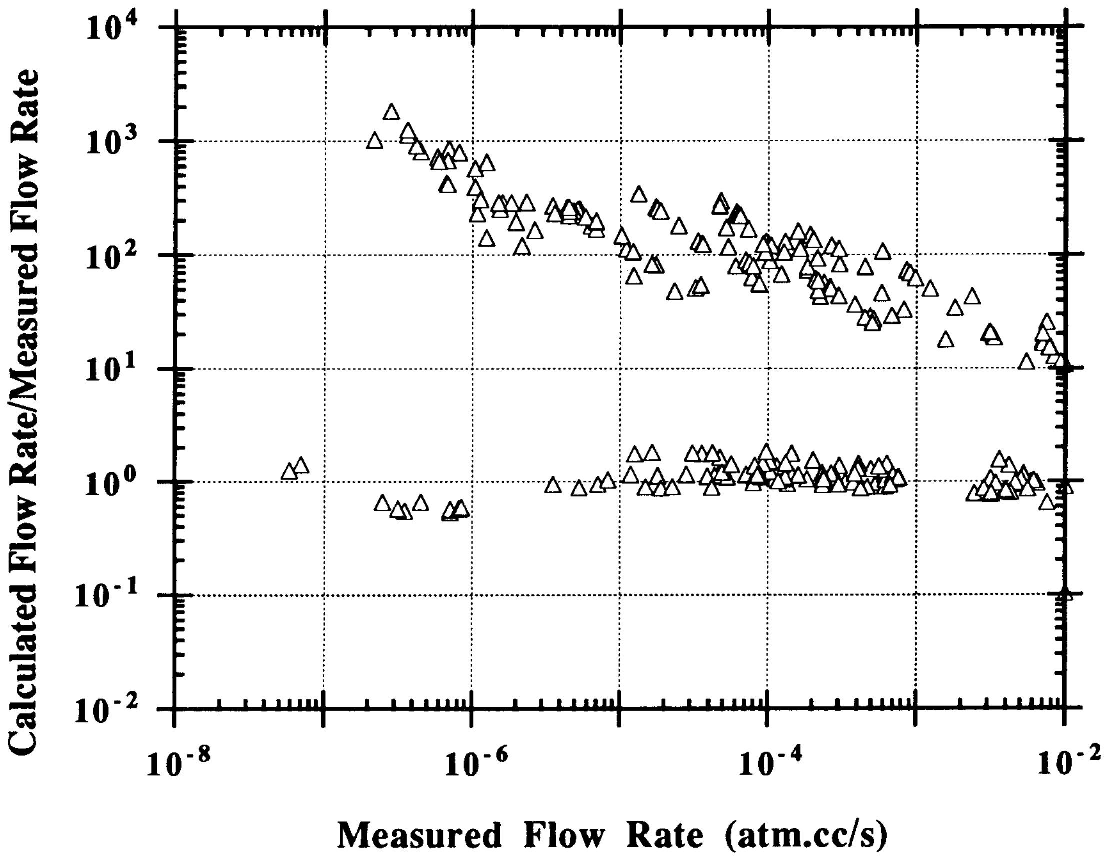

Figure 2. Measured gas flow rate versus the ratio of the predicted gas flow rate to the measured gas flow rate. Data taken from Figure 1.

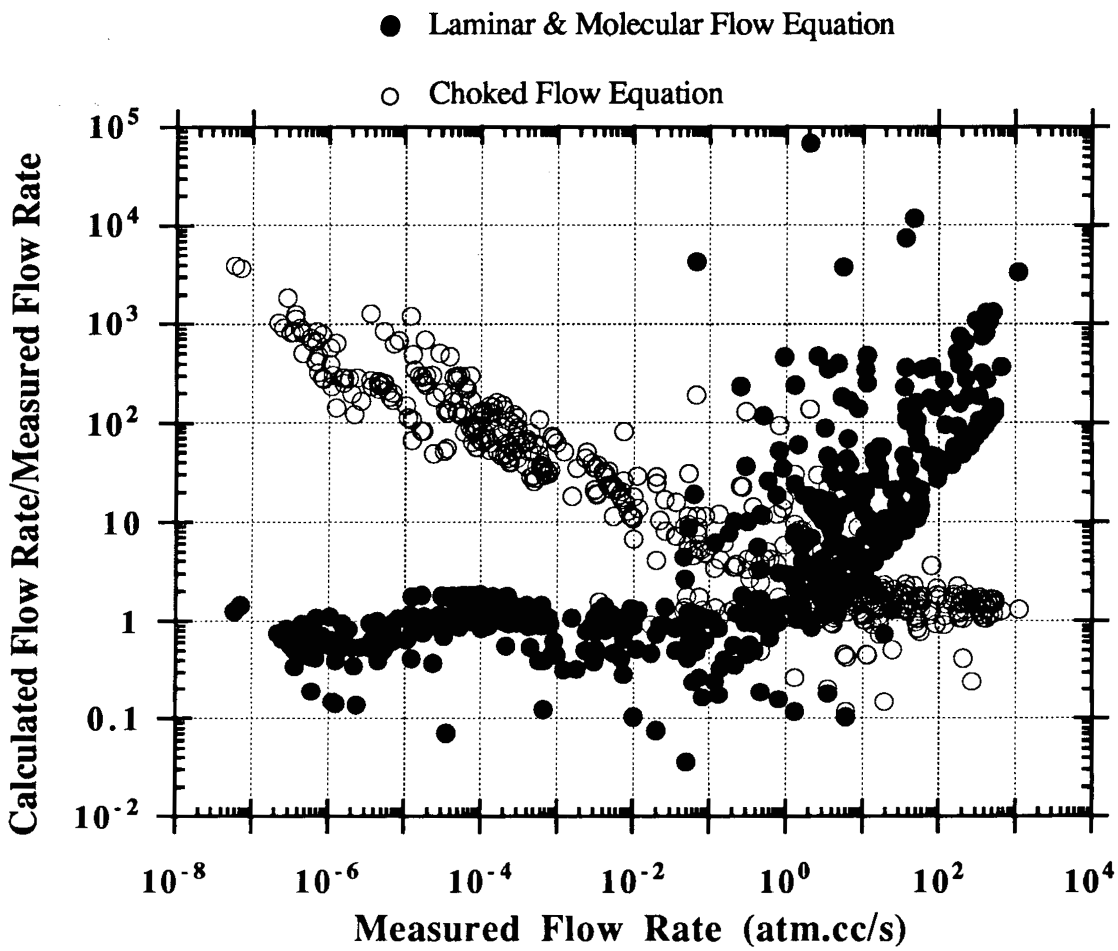

Figure 3. Measured flow rate versus the ratio of the calculated flow rate to the measured flow rate. The two predictive equations were applied globally to the complete gas-flow-rate data set.

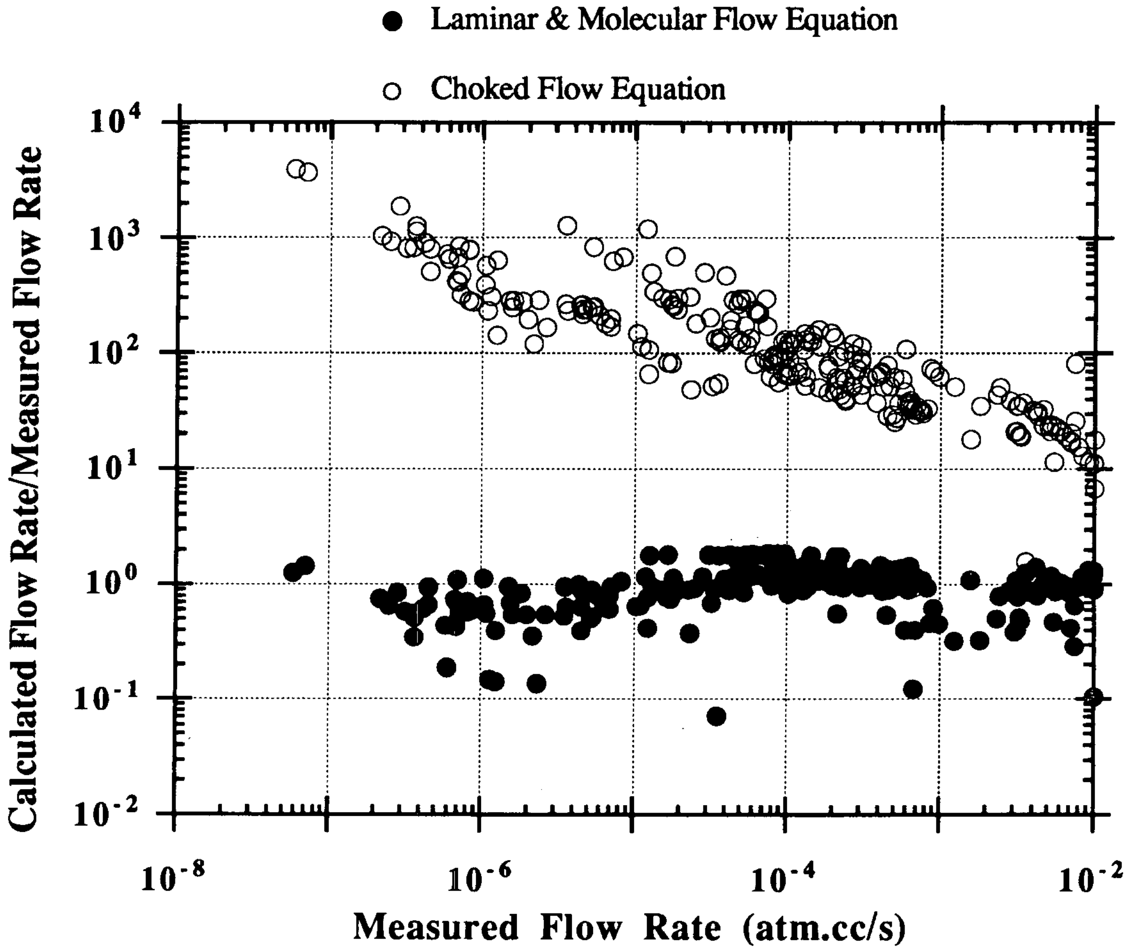

Figure 4. Measured flow rate versus the ratio of the calculated flow rate to the measured flow rate. The two predictive equations were applied globally to the complete gas-flow-rate data set. Data from Figure 3.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

Experimentally measured gas flow rates obtained from the literature were compared to the predictions obtained using the constitutive flow equations given in ANSI N14.5, the "American National Standard for Radioactive Materials-Leakage Tests on Packages for Shipment,," to determine whether the equations apply to the predictions of gas flow rates from leaking containment vessels used to transport radioactive materials.

The equations were applied to both (1) the data set according to the recommendations given in ANSI N14.5, and (2) globally to the complete data set. It was found that:

* For flow rates $\leq$ 1 atm·cm^3/s, the predictions obtained with the continuum and molecular flow equation provided good agreement with the experimental values and the choked flow equation resulted in over-prediction of the measured values.

* For flow rates > 1 atm·cm^3/s, the molecular and continuum flow equation over-predicted the measured flow rates and the predictions obtained with the choked flow equation agreed well with the experimental values.

Since leakage rates from packages used to transport radioactive materials are almost always <1 atm·cm^3/s, it is suggested that the continuum and molecular flow equation be used for gas flow rate predictions related to these applications.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Gas
Flow
Micro-capillary
Micro-orifice

13. AVAILABILITY STATEMENT

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14. SECURITY CLASSIFICATION

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